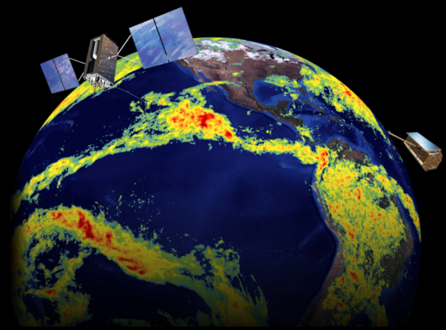
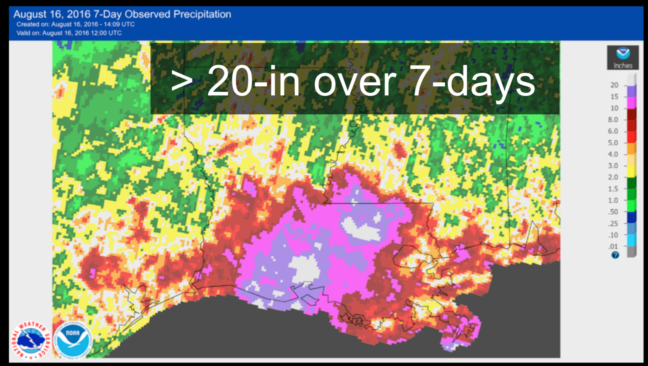
Remote Sensing of Extreme Precipitation and Moisture: Synergies Between GPM and Other Sensors





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CGMS/WMO International Precipitation Working Group (IPWG-9)
Seoul, Korea, 5-9 November 2018

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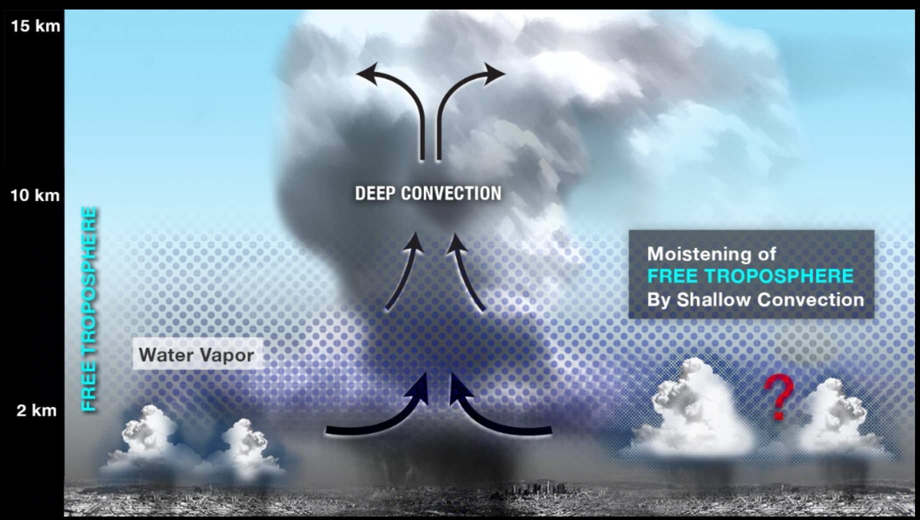
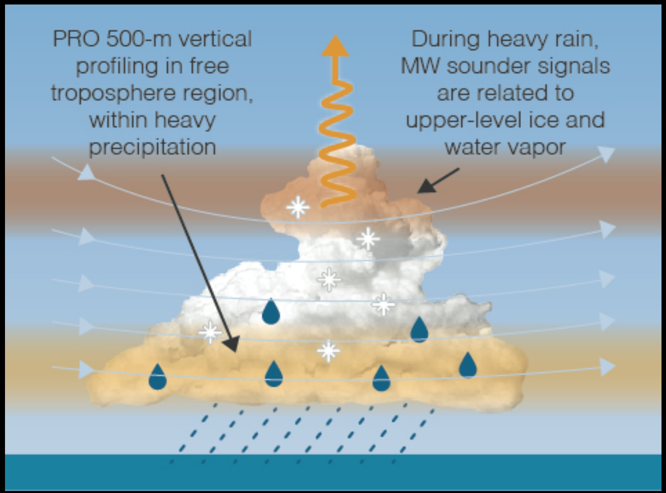
Water Vapor Conditions and Extreme Precipitation

Extreme precipitation is a key variable for societal impacts in weather forecasting and climate projections. The role of the vertical structure of moisture in the immediate environment of the convection has been identified as a leading factor in controlling extreme events.



Increasing evidence points to control of convection by moisture in the *free troposphere* — strengthening it, when abundant, by making the atmosphere more unstable, or weakening the convection when entraining dry air from these layers and decreasing the buoyancy (*Schiro et al.*, 2016)

Science investigations have been hindered since the direct measurement of the water vapor profile internal to known heavy precipitation has not been systematically measured before.



Water Vapor Conditions and GPM Algorithms

The moisture/temperature environment plays a direct role in the design and execution of GPM radar and radiometer algorithms (e.g., *a-priori* separated by 2-m air temperature, water vapor)

Using stability-based quantities (eg, CAPE) shown to improve over-land radiometer performance over land (Petković et al 2018)

For open ocean, very limited independent ground validation (GV) sources, away from coastal radar coverage:

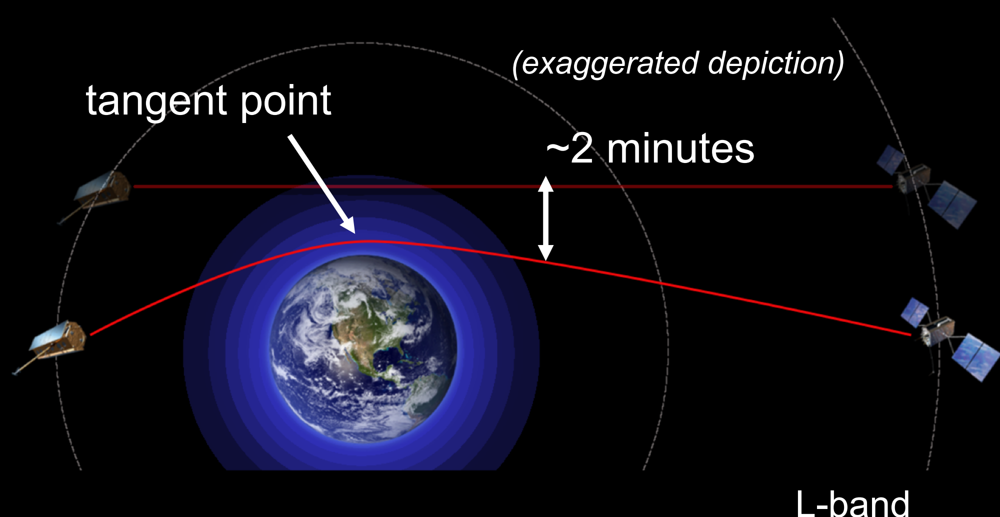
- OceanRain (Klepp, 2015, presented IPWG-9 this week)
- Tropical Mooring Arrays (Serra, 2017, presented at IPWG-8)
- Argo floats with acoustic rain gauges (eg, Pensieri et al, 2015)

Utilization of non-traditional sources and comparison metrics to evaluate GPM data products over ocean

Global Navigation Satellite System (GNSS) Radio Occultations (RO)

Dedicated L-band (near 1.4 GHz) GNSS receivers track the GNSS (GPS, Galileo, GLONASS etc) phase delay as they occult (rise or set) behind the Earth.

- The signal is bent due to the index of refraction gradients in the atmosphere
- RO receivers precisely track the time derivative of the phase between consecutive measurements (**Doppler shift**).
- After removing geometric effects due to relative motion of the two involved satellites, the atmospheric bending angle can be inferred.



High vertical resolution (~200m), global distribution, all weather capability; coarse along-ray resolution (~100 km)

Excess phase

↓

Bending angle α

Spherically symmetric atmosphere ↓ Inverse Abel transform

Index of refraction *n(z)*

Variational analysis ↓ T from models to infer q

T(z), q(z)

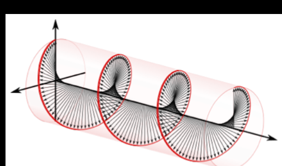
Polarimetric Radio Occultations (PRO) Concept

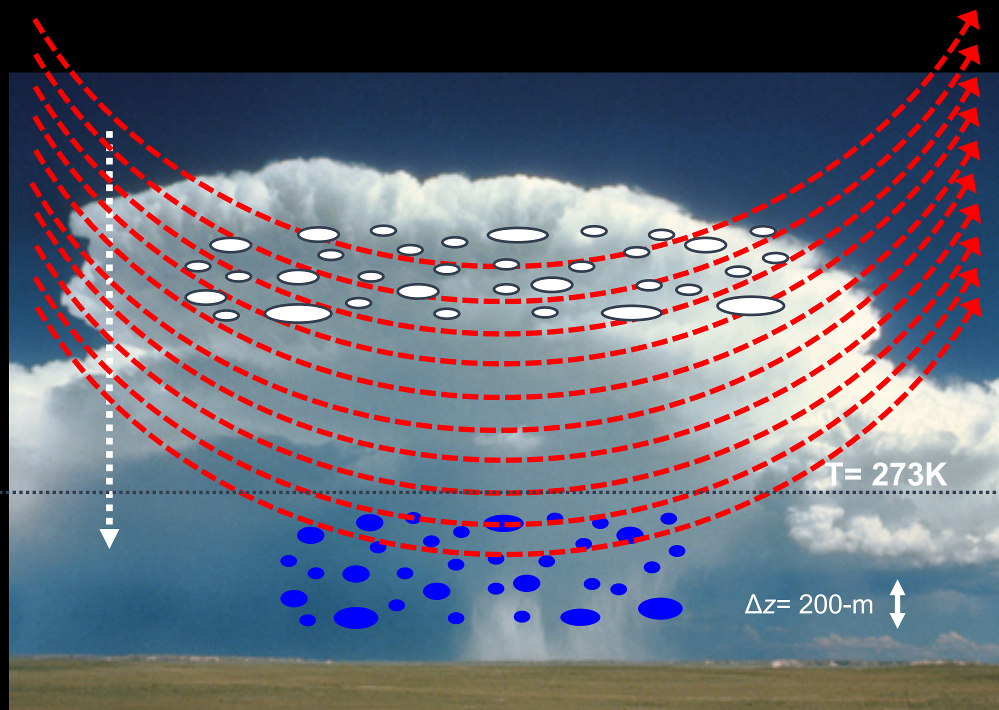
GNSS (L-band) propagation through precipitation induces a cross-polarized component, measured as a differential phase delay (analogous to ϕ_{DP} measured by the US polarimetric NEXRAD radars, but only 1-way)

Potential to extend the capabilities of normal RO, with ***simultaneous*** measurements of the profile of water vapor (q), temperature (T) and an *indication* of heavy precipitation (P), along each ray

T(z), q(z) + P(z)

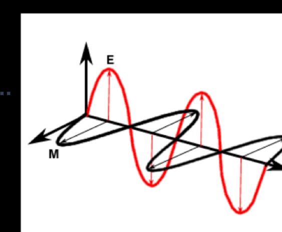
GNSS
RHC transmit





Simultaneous
H/V receive

q(z), T(z), P(z)



ROHP – PAZ experiment

Radio **O**ccultations and **H**eavy **P**recipitation with **PAZ** satellite

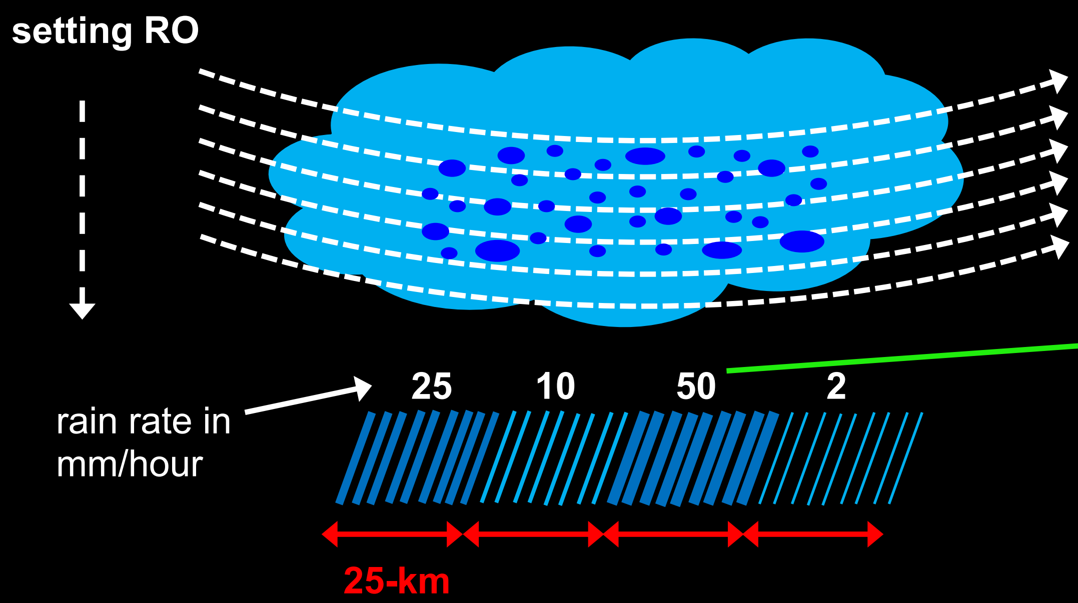
rohp-PAZ

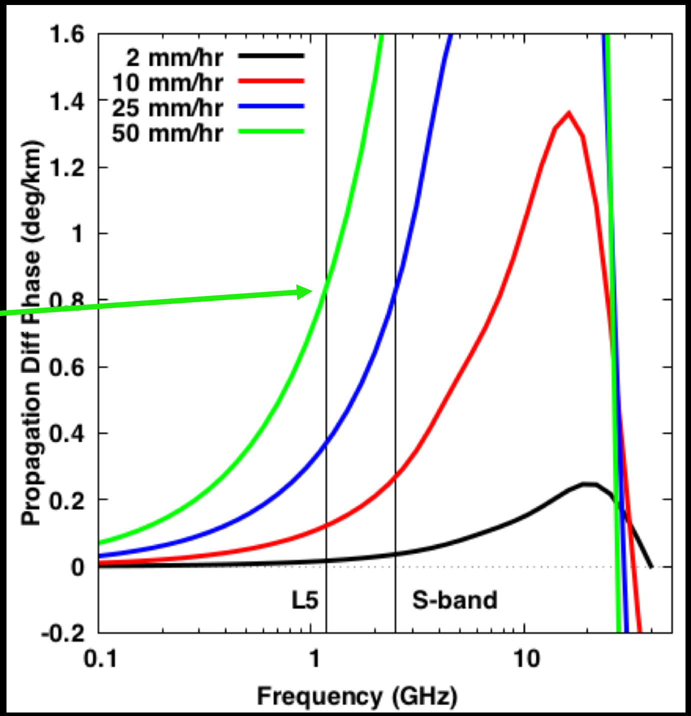
P.I. : Dr. Estel Cardellach (ICE – IEEC/CSIC, Barcelona)

- International science team with major operational agencies (NOAA, ECMWF, etc)
- Proof of concept experiment to test polarimetric radio occultations from space
- PAZ was launched on **Feb 22th 2018** by SpaceX/Falcon-9 out of Vandenberg AFB
- First ever pol-RO data from space are being assessed at this time

Cardellach et al. 2015, IEEE Trans. Geosci. Rem. Sens.
Cardellach et al. 2017, QJ Royal Meteor. Soc.
Padullés, et al, 2018, Atmos. Chem. Phys..
Tomas et al, 2018, IEEE Trans. Geosci. Rem. Sens.

Relating Polarimetric Phase Difference to Precipitation





Total polarimetric phase shift due to rain is a path-weighted sum =

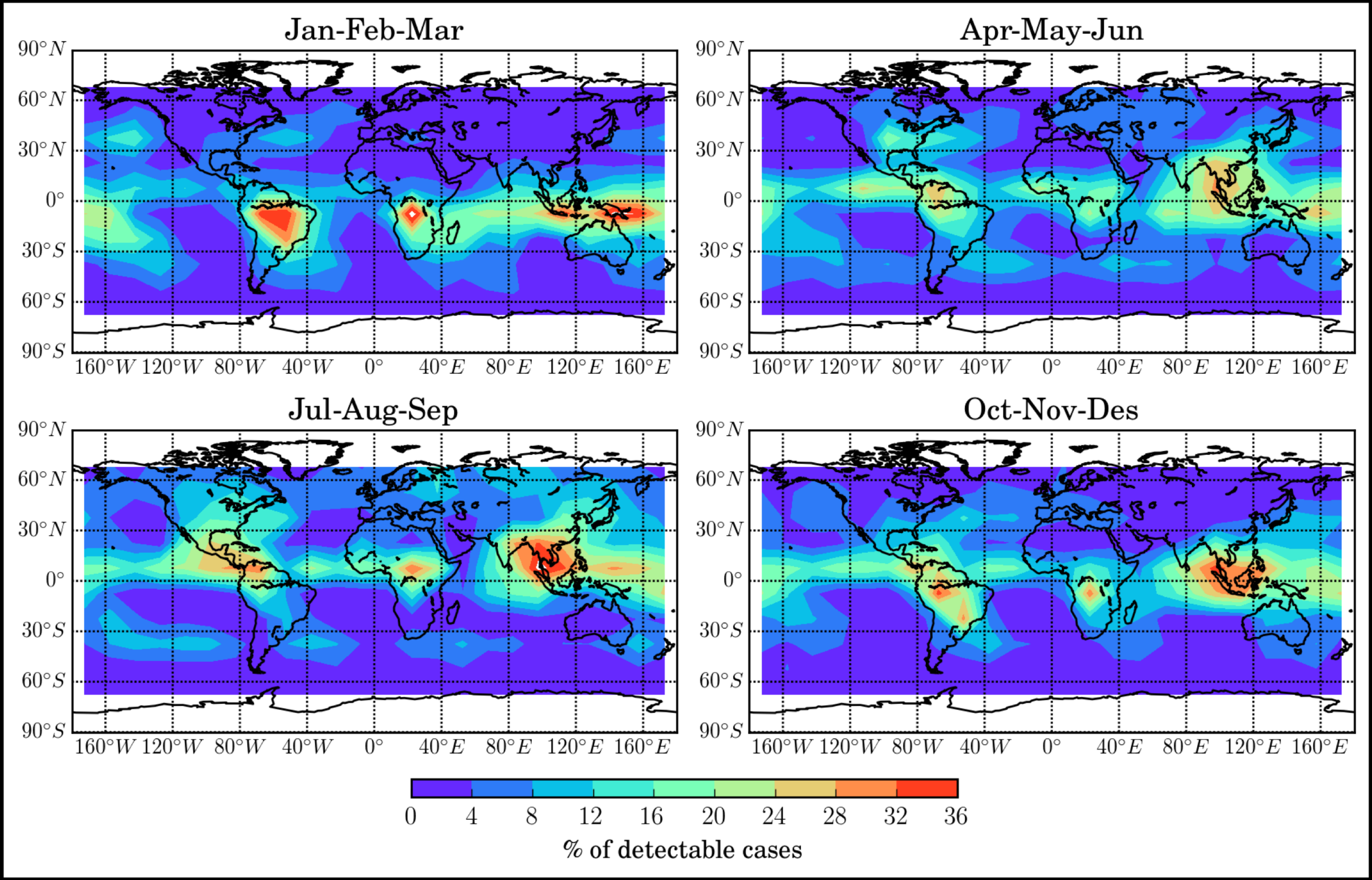
0.35(25) + 0.1(25) + 0.8(25) + 0.05(25)= 14.5 deg= 5 mm

Assuming -3dB performance with respect to COSMIC equipment, PAZ will detect precipitation events inducing $\Delta\phi > 1.5$ mm.

This value would clearly indicate the presence of heavy precipitation along the ray path, but the rain structure is non-unique. Different path lengths and rain intensities could yield a similar phase difference.

ROHP – PAZ experiment

How often does $\Delta\phi$ > 1.5 mm?



Differential phase observable

rohp-PAZ

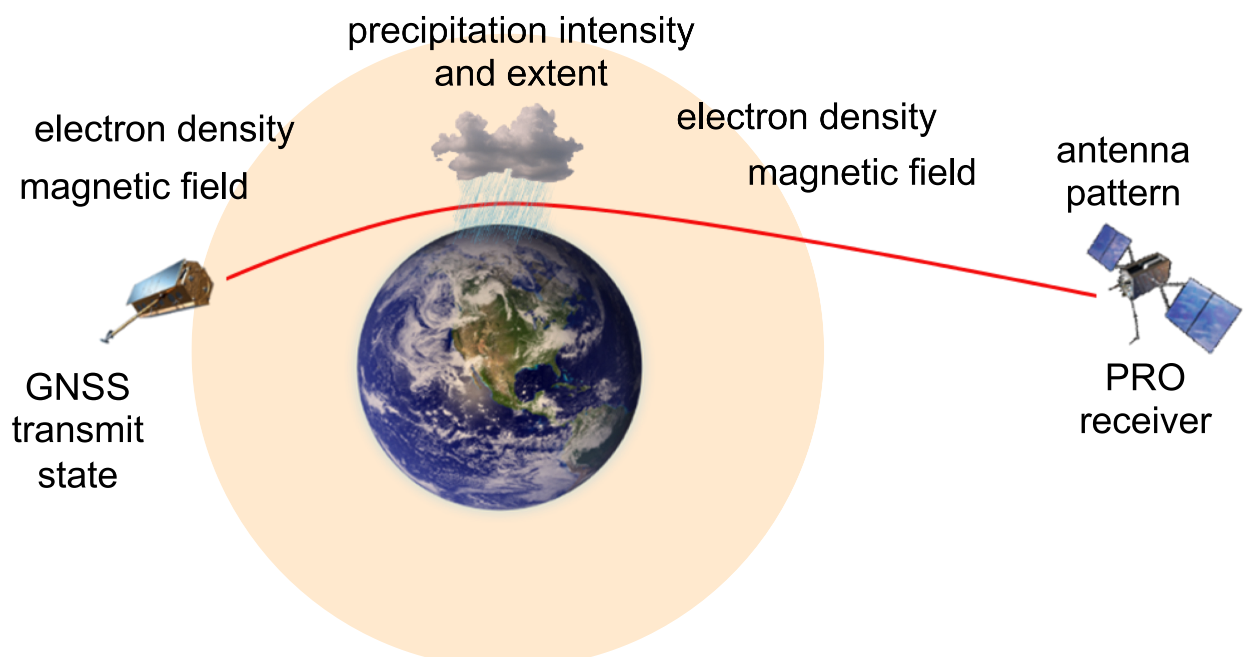
Many factors contribute to the full end-to-end received signal

emission state
precipitation intensity
precipitation extension
electron density
magnetic field
antenna pattern
receiver

$$\Delta\Phi = \Delta\Phi\left(E, K_{dp}, L, n_e, \vec{B}, A, R\right)$$

R. Padulles, Ph.D. dissertation, Univ. of Barcelona, 2017

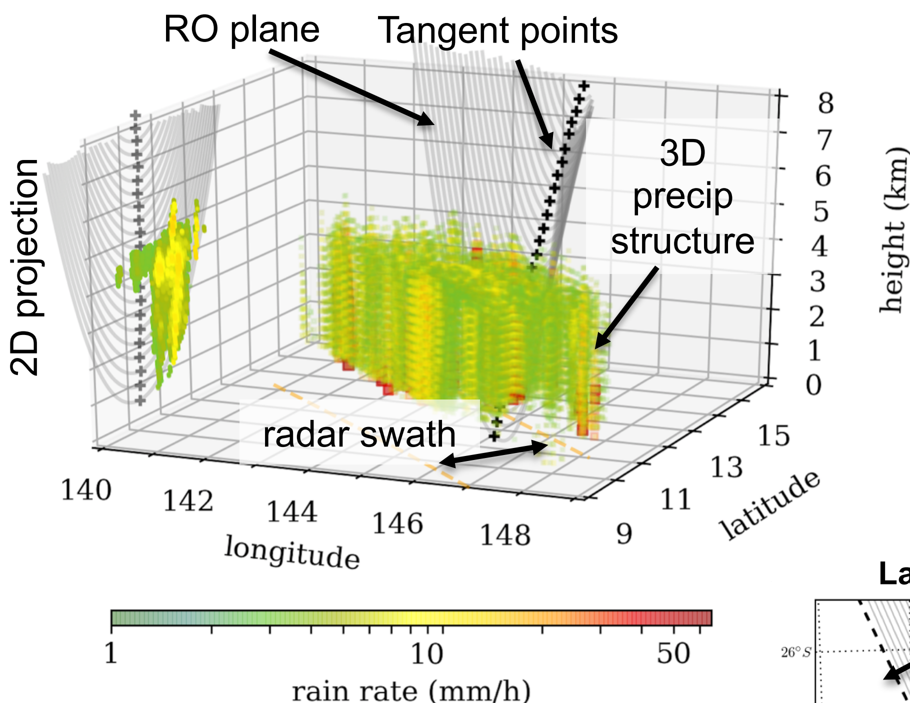
$$\mathbf{E} = e^{-i\Phi}\,\frac{e^{-ikr}}{r}\begin{bmatrix}1 & 0\\ 0 & e^{i\phi_{arc}}\end{bmatrix}\begin{bmatrix}a_{\mathrm{hh}} & 0\\ 0 & a_{\mathrm{vv}}e^{i\phi_{\mathrm{ant}}}\end{bmatrix}\mathbf{R}(\Omega_2)\begin{bmatrix}e^{-ik_h} & 0\\ 0 & e^{-ik_v}\end{bmatrix}\mathbf{R}(\Omega_1)\;\mathbf{E}^{\mathrm{i}}{}_{\{\hat{e}_h,\,\hat{e}_v\}}$$

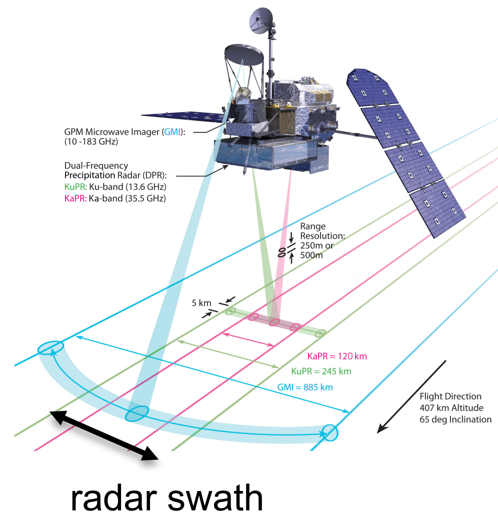


JPL

Modeling ROHP with TRMM/GPM radar data, using realistic rain/ice particle shapes and ray tracing

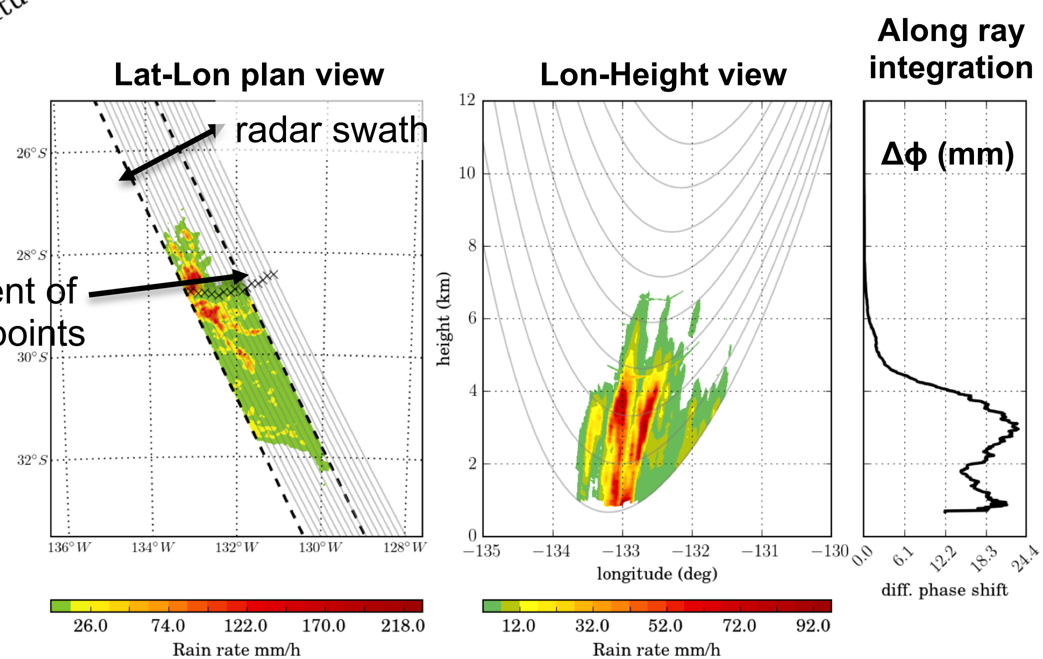
rohp-PAZ





$$\Delta\Phi_{precip} = \int_L K_{dp}(l)dl$$

$$K_{dp} = \frac{\lambda^2}{2\pi}\int_{D_1}^{D_2} \Re\{S_h(D) - S_v(D)\}N(D)dD$$



Cardellach et. al, 2017
(QJRMS IPWG-8 special issue)

JPL

First Six Months of ROHP data

rohp-PAZ

Currently collecting approx. 150 PRO profiles per day

Data are processed by CSIC/JPL for polarimetric science analysis

As a first test, each ROHP PRO profile was paired with its nearest 30-min IMERG and global IR data

(PRO complements IMERG with vertical profile information, IMERG helps validate the usefulness of the PRO concept)

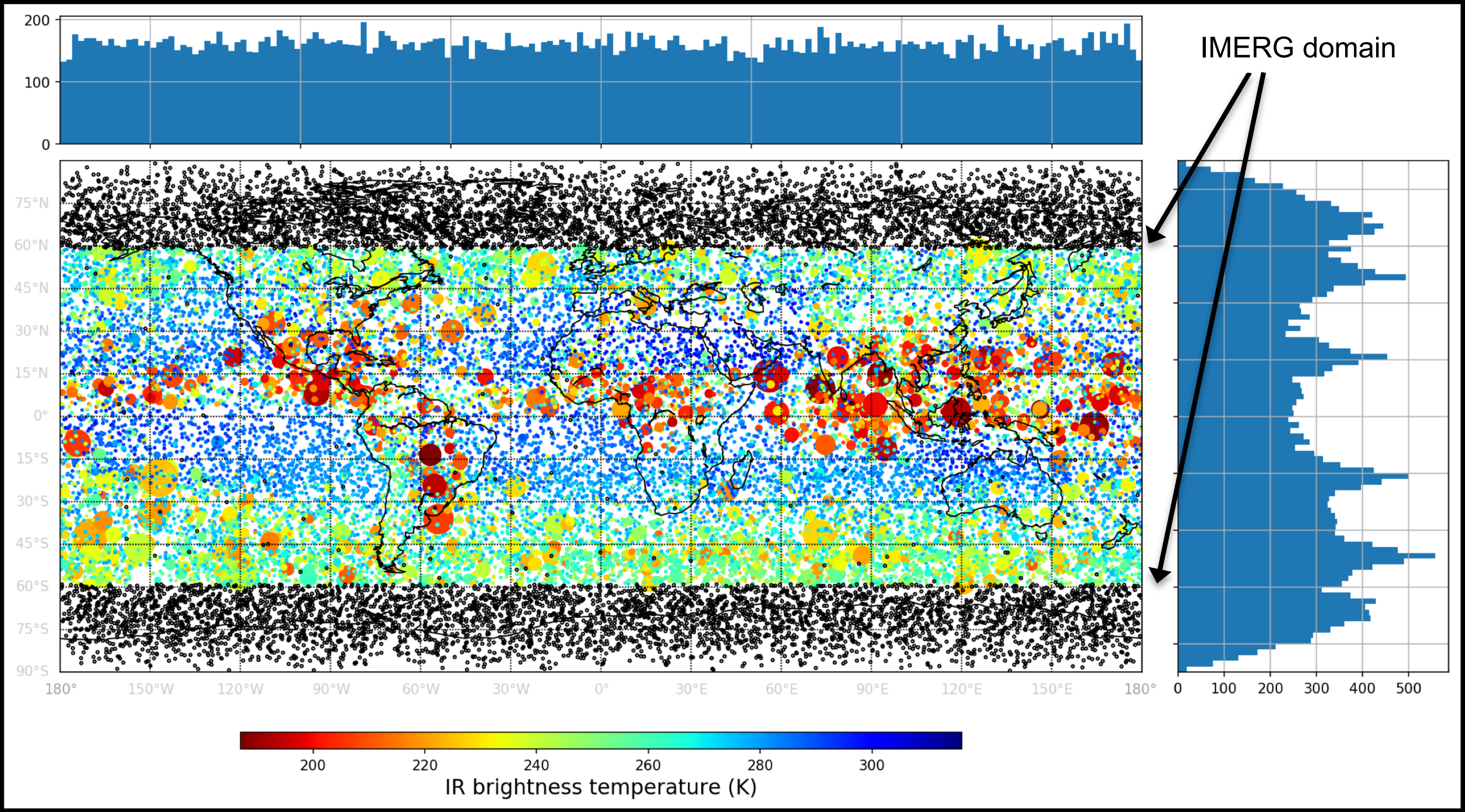
For selected PRO, nearby +/-15 min coincidences with GPM were identified and vertical precipitation structure assessed

(GPM informs PRO of the 3D structure of the precipitation cells, and PRO informs GPM on the thermodynamical context within the precipitating regions)

Conditional statistics of PRO delta-phase were prepared

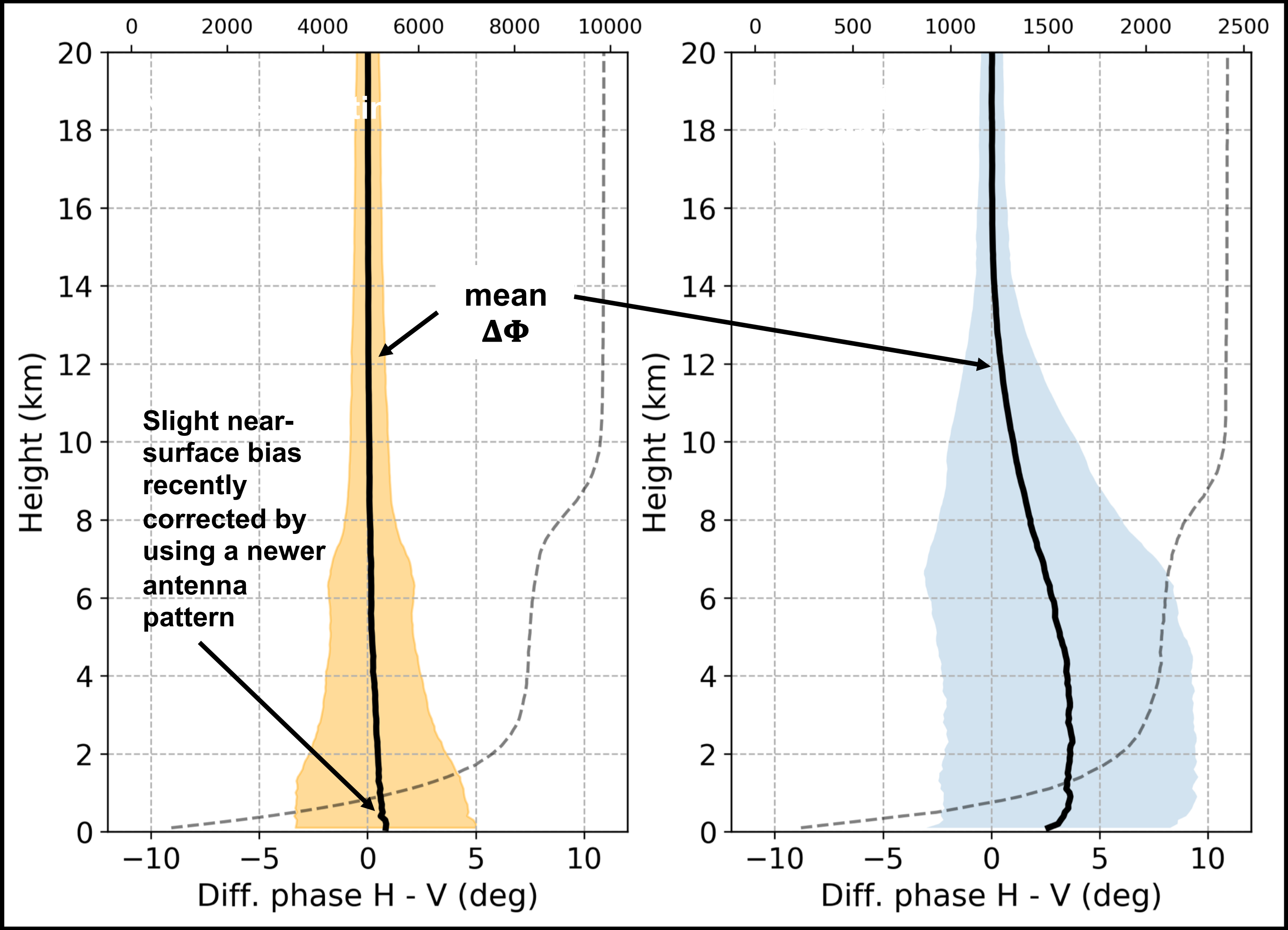
ROHP - PAZ data – IMERG/IR co-locations

2018/05/10 - 2018/10/24 (N=28849)



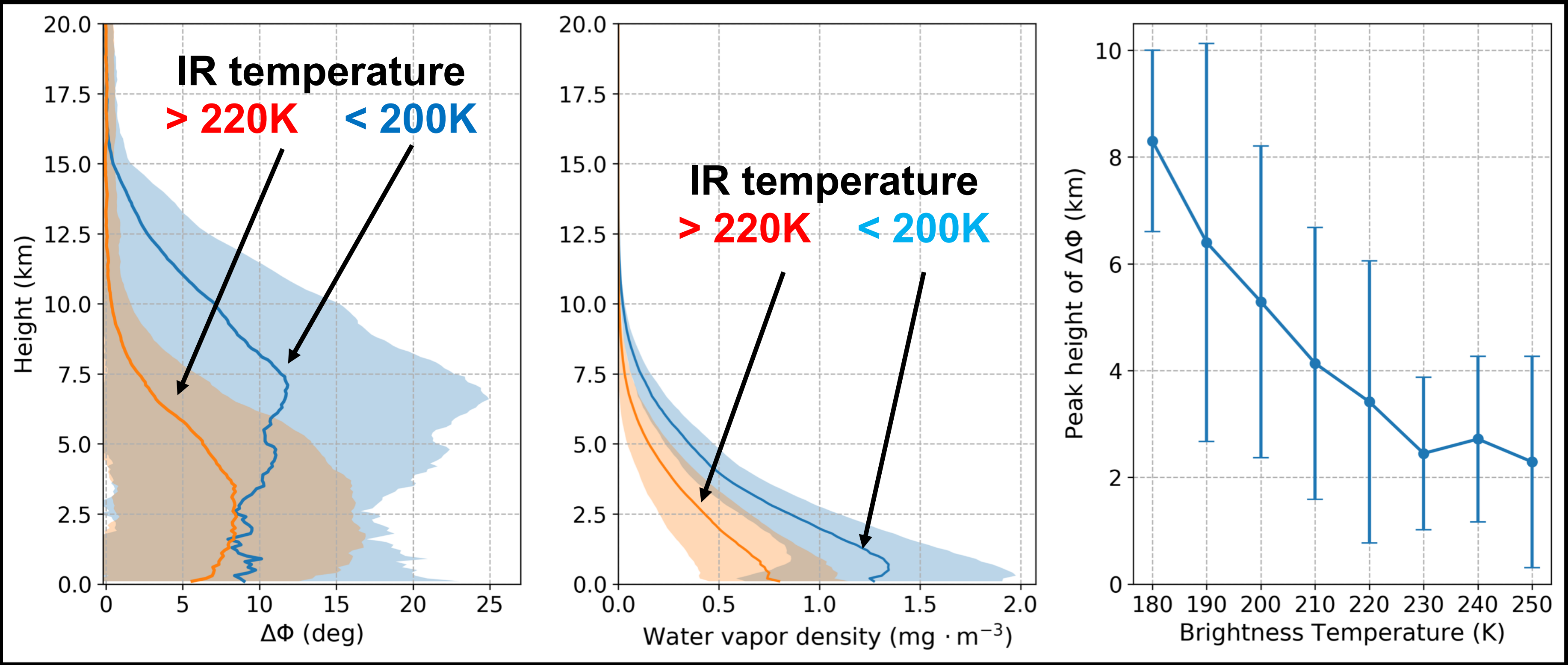
- Color corresponds to IR temperature (inverted, red=colder)
- Size of symbol corresponds to intensity of nearest 30-min IMERG rain rate

ROHP data to date, using nearest 30-min IMERG as a rain/no-rain separation



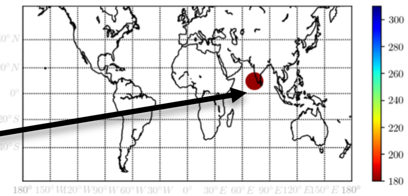
ROHP data to date, using 30-min geo-IR for separation

Mixed phase and upper level ice detection?

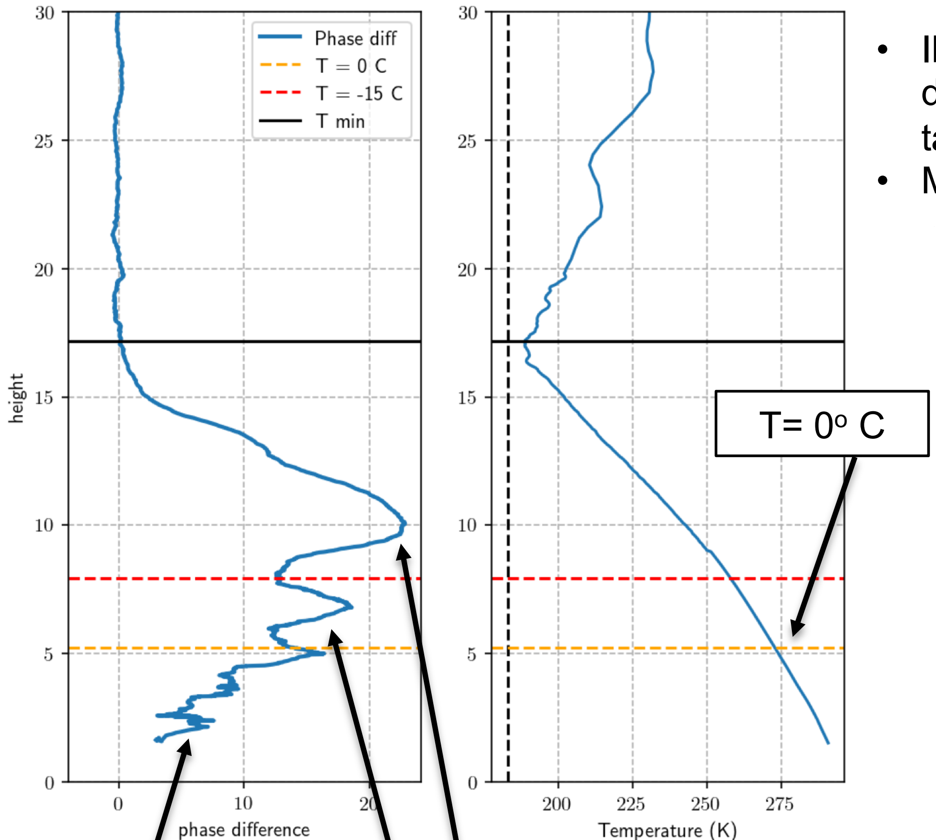


ROHP - PAZ data
Interesting cases

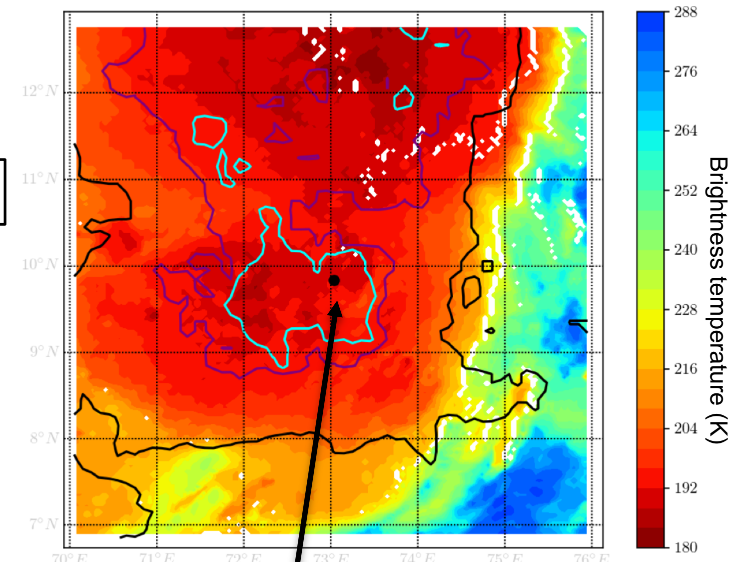
location of near-surface tangent point



rohp-PAZ



- IMERG rain rate (averaged over a 2x2 deg area surrounding the near-surface tangent point) = **8.4 mm/h**
- Minimum brightness temperature = **183 K**



liquid phase

significant depolarization in ice region, and through mixed phase

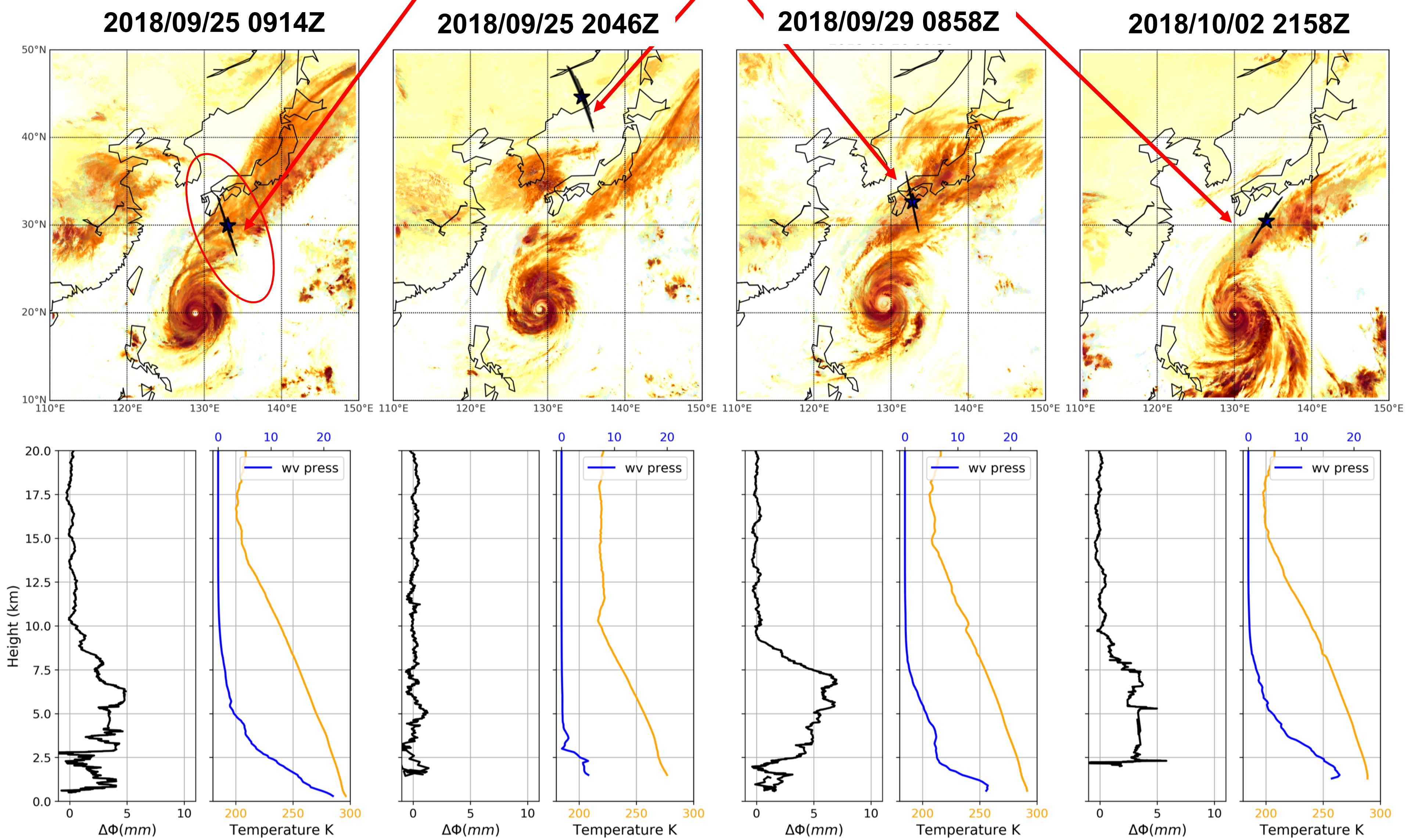
Near-surface tangent point (middle of figure)

JPL

Typhoon Trami

rohp-PAZ

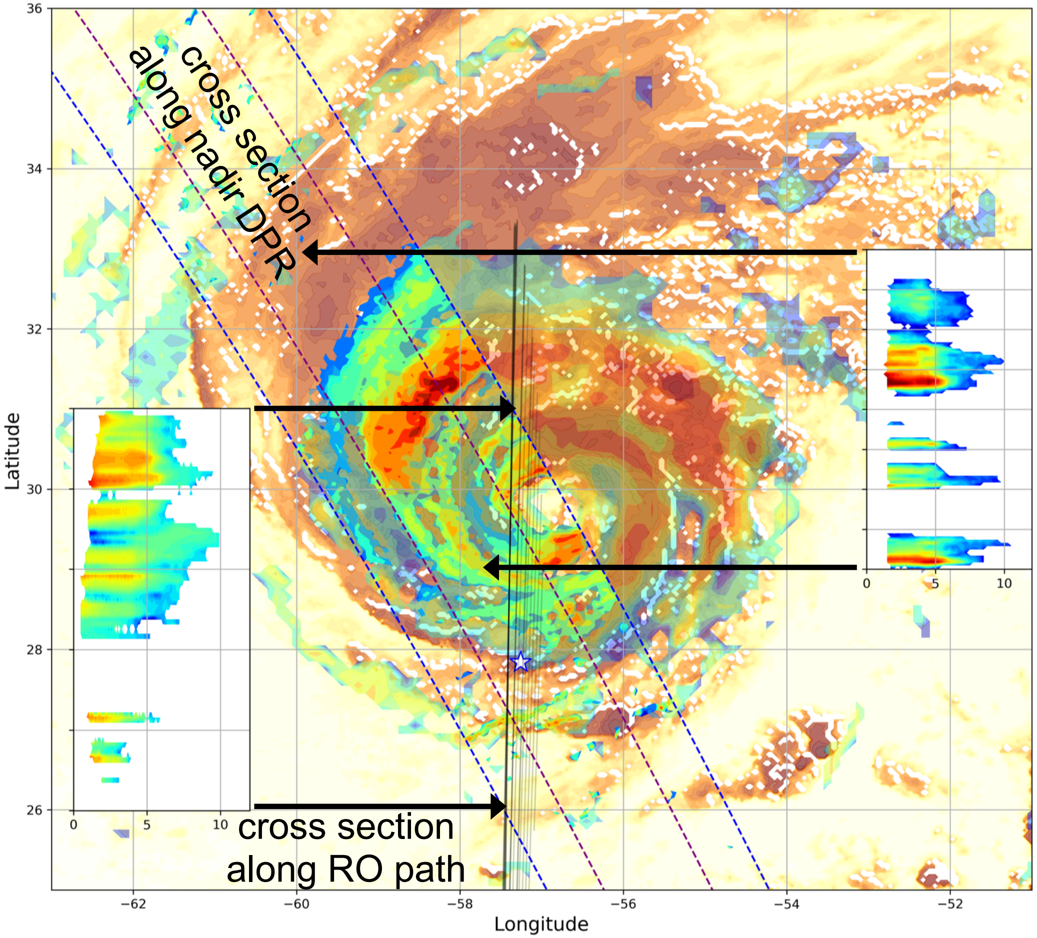
surface projection of ray path, star indicates tangent point)

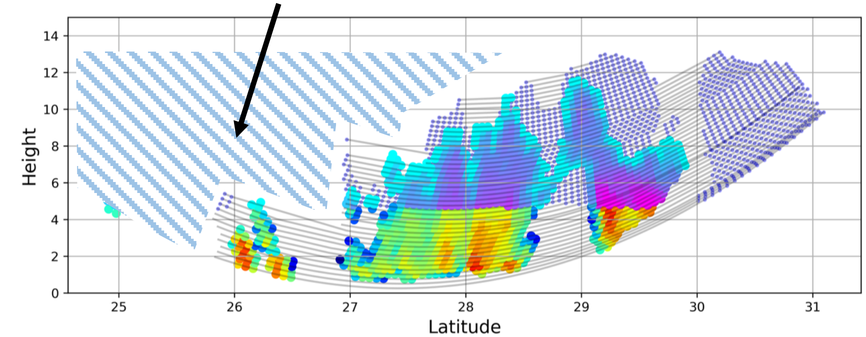


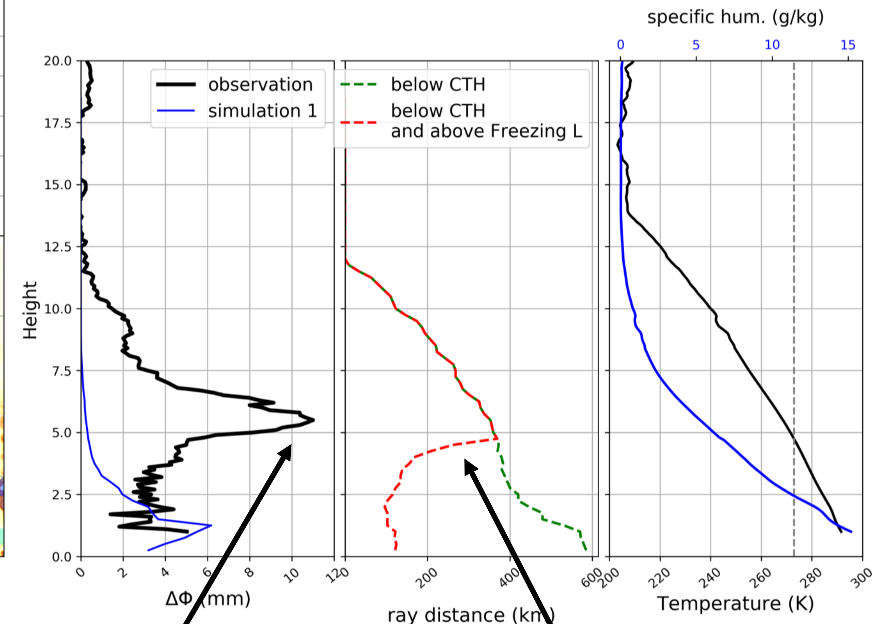
JPL

Hurricane Leslie

Maybe clouds, but below DPR sensitivity?







Peak in Δϕ occurs when the full ray path propagates above the freezing level

red=ray distance below cloud top height, and above freezing level

Recent Publications and Proceedings

rohp-PAZ

Cardellach, E., and co-authors, 2018: Sensing heavy precipitation with polarimetric radio occultations. *Geophy. Res. Lett.*, in review.

Tomás, S., R. Padullés, E. Cardellach, 2018: Separability of systematic effects in polarimetric GNSS radio occultations for precipitation remote sensing. *IEEE Transactions on Geoscience and Remote Sensing*, 56, 4633-4649.

Padullés, R., Cardellach, E., Wang, K. N., Ao, C. O., Turk, F. J., and de la Torre-Juárez, M., 2018, Assessment of GNSS radio occultation refractivity under heavy precipitation, *Atmospheric Chemistry and Physics Discussions,* https://doi.org/10.5194/acp-2018-66.

Padullés, R., F.J. Turk, C.O. Ao, and M. de la Torre, 2018: Vertical thermodynamic characterization of heavy precipitation using GNSS Radio Occultation observations. *4th International Conference on GPS Radio Occultation*, April, Taiwan.

Cardellach, E., S. Tomás, S. Oliveras, A. Rius, B. Schreiner, J. Weiss, J.Clapp, M. Seymour, C.O. Ao, F.J. Turk, M de la Torre-Juárez, R. Padullés, K-N Wang, F. Cerezo, 2018: The Radio Occultation and Heavy Precipitation experiment aboard PAZ (ROHP-PAZ): after launch activities. *4th International Conference on GPS Radio Occultation*, April, Taiwan.

Cardellach, E., Padullés, R., Tomás, S, Turk, F. J., Ao, C. O., and de la Torre-Juárez, M., 2017, Probability of intense precipitation from polarimetric GNSS radio occultation observations, *Q. J. Royal Meteorological Soc*iety, 12, 10.1002/qj.3161

Turk, F. J., Ao, C. O., de la Torre Juárez, M., Cardellach, E. and Padullés, R. and Tomás, S., 2017, GNSS Polarimetric Radio Occultations: Thermodynamical Structure within Precipitation, AMS 97th annual meeting, Seattle.

Padullés, R. Cardellach, E. de la Torre Juárez, M., Tomas, S., Turk, F. J., Oliveras, S., Ao, C. O. and Rius, A., 2016, Atmospheric polarimetric effects on GNSS Radio Occultations: the ROHP-PAZ field campaign, *Atmospheric Chemistry and Physics*, 16, 635-649, 10.5194/acp-16-635-2016

Cardellach, E., Tomás, S., Oliveras, S., Padullés, R., Rius, A., De la Torre-Juárez, M., Turk, F.J., Ao, C.O., Kursinski, E.R., Schreiner, B., Ector, D. and Cucurull, L., 2014, Sensitivity of PAZ LEO Polarimetric GNSS Radio-Occultation Experiment to Precipitation Events, *IEEE Transactions on Geoscience and Remote Sensing*, 53,190-206, 10.1109/TGRS.2014.2320309

Applications and Way Forward

1) Knowledge of the moist thermodynamic profile within precipitation may be useful to evaluate the convective parameterizations used in climate and forecast models.

2) ROHP data can be inverted to estimate the conditional probability that the path-averaged P exceeded a threshold. Could contribute to evaluation of GPM products for the instances of extreme rain (particularly over ocean).

3) A cubesat version of the receiver (Cion) has successfully flown on CICERO*. Unique RO orbit strategies, observing geometries, etc are conceivable.

4) Advance RO forward observation operators and increased assimilation of rain-affected data in NWP forecast models.

5) Independently assess water vapor-precipitation relationships amongst various climate models.

6) Improved depiction of 3-D water vapor structure from fusion of increasingly dense constellations of RO and ATMS-like passive MW sounders.

*CICERO (Community Initiative for Continuing Earth Radio Occultation)

Challenges in lower troposphere/PBL

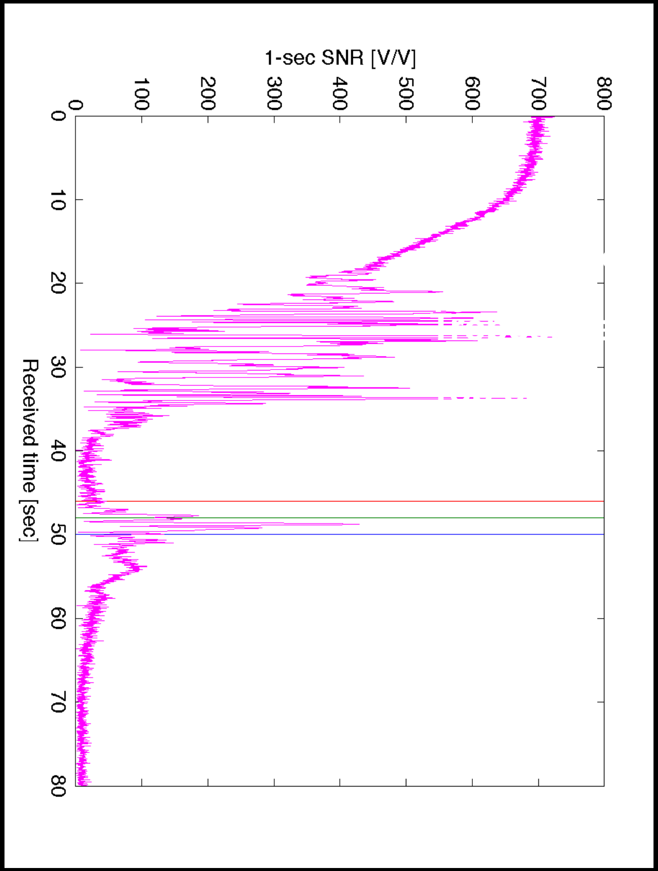
- Large vertical gradient causes strong defocusing → low SNR
- Diffraction and atmosphere multipath -> strong phase fluctuations

Which may lead to…

- Retrieval bias
- Profile truncation

These problems are most prevalent over moist regions.

New receiver technologies are designed with a large beam-forming antenna array (higher SNR).



Anticipated ROHP products

From phase observable to precipitation information